Magnetic Structure at Buried Interfaces

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One of the central issues in nanomagnetism is the magnetic behavior at interfaces. Many new magnetic materials and devices rely on the interplay between different magnetic properties [1]. Examples of these are, exchange bias systems (combining ferromagnetic and antiferromagnetic materials), exchange spring magnets (hard and soft ferromagnets), proximity effects between superconductors and ferromagnets, artificial multiferroics (ferromagnetic and ferroelectric materials), and spin-injection from ferromagnetic to non-magnetic heterostructures. In most of these cases a detailed understanding of the magnetic structure is highly desirable in order to understand the underlying phenomena satisfyingly. This point will be highlighted with several selected examples. The first set of examples show studies of equilibrium magnetization structures, while the second set of examples focuses on non-equilibrium phenomena.

One question germane to studies of magnetic heterostructures is whether magnetic order in one material induces magnetic order in a nominally non-magnetic material. Possible candidates for such a magnetic proximity effect are highly susceptible materials such as Pd and V, which are on the verge of becoming ferromagnetic. While it is well established, that a net magnetic moment can develop in Pd and V when they are in contact with ferromagnetic materials, Manago *et al.* suggested that Pd can even become ferromagnetic when coupled to an antiferromagnet such as NiO [2]. Using polarized neutron reflectometry we investigated NiO/Pd heterostructures for the presence of an induced ferromagnet moment in Pd [3]. Using a specific isotope mixture of Ni in the preparation of NiO, the chemical contrast across the Pd/NiO interface was greatly suppressed, thus enhancing sensitivity to magnetic contrast at the reflecting interface. Despite the enhanced sensitivity, no evidence for a proximity effect was observed. If present, the magnetic moment per Pd atom could not be more than $0.01\mu_B$, regardless of Pd layer thickness, crystalline interface orientation, and number of NiO/Pd bilayers.

The interplay between ferromagnetism and superconductivity has generated significant research interest, since the competition between these generally mutually exclusive types of long-range order gives rise to a rich variety of phenomena. While these have been mostly studied in simple metallic alloys, there has been recently a lot of interest in complex oxide systems consisting of high-T_c superconductors and colossal magnetoresistive manganites. Both of these materials have physical properties that depend very sensitively on the charge carrier density and thus the interface properties may deviate significantly from bulk behavior. In particular, in $La_{0.7}Ca_{0.3}MnO_3$ (LCMO) / $YBa_2Cu_3O_{7-\delta}$ (YBCO) superlattices it is observed that the saturation magnetization is well below the bulk value of LCMO. Using polarized neutron reflectometry we could show that this reduced magnetization originates from a suppressed magnetization at the LCMO/YBCO interface. Additional atomically resolved electron energy loss spectroscopy suggests that this magnetization suppression is due to a significant charge transfer across the interface, which may give rise to antiferromagnetic order at the interface.

The coupling between an antiferromagnetic and ferromagnetic material can give rise to exchange bias, manifesting itself in a magnetic hysteresis curve, which is not symmetric around zero magnetic field. This effect is of fundamental importance to magneto-transport applications, since it allows establishing a reference magnetization direction. However, there are still ongoing controversies about its microscopic origin. One question in particular is whether there is a net magnetic moment in the antiferromagnet at the interface with the ferromagnet. We have studied this question in a Co/$LaFeO_3$ exchange bias system [4]. In the exchange biased state we observe differences between the polarized neutron reflectivity profiles when the magnetization of the ferromagnetic layer is saturated either parallel or antiparallel to the cooling field. This difference vanishes above the blocking temperature. Since the reflectivity profiles are directly related to the Fourier components of the magnetization depth profile, this data suggest that a net moment develops within the antiferromagnetic layer close to the interface with the ferromagnetic layer, which remains unchanged during the magnetic-field cycling. Furthermore, this net moment is coupled antiferromagnetically to the ferromagnet.

Exchange bias systems are also a good example for metastable magnetization structures. In many exchange bias systems the exchange bias is reduced upon subsequent field cycling. Recent numerical simulations based on a simple coherent rotation model suggest that the symmetry of the anisotropy in the antiferromagnet plays a crucial role for the understanding of these training effects in exchange bias systems [5]. Namely, the existence of more than one antiferromagnetic easy anisotropy axes can stabilize a non-colinear arrangement of the antiferromagnetic spins after the initial field-cooling, which relaxes into a collinear arrangement after the first magnetization reversal of the ferro-magnet. A quantitative detection of the concurrently changing net moment in the antiferromagnet would directly confirm this model.

Another important non-equlibrium phenomenon is spin-injection from a ferro-magnetic into a non-magnetic material. Spin-injection is the basis for a variety of different magnetotransport effects, such as giant magnetoresistance and spin-torque transfer effects. Recently it has also been shown that spin-injection can be observed in lateral spin-valve structures. Using a planar 2-dimensional geometry has several advantages. It allows for more flexibility in tailoring the magnetic properties of the ferro-magnetic components through their shape-anisotropy. More importantly, if the spin-polarization in the nominally non-magnetic component can be imaged directly, i.e., through circular magnetic dichroism, then a real space image of the spin-diffusion could be obtained.

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